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14. ABSTRACT

During the program, both 4x4 and 8x8 SiC APD arrays have been demonstrated with world-record single photon detection efficiency (SPDE) and dark count rate (DCR). Further advancements have been made with initial work exploring micro-lenses to enhance APD array performance, as well as the demonstration of APDs with 40% single photon detection efficiency (SPDE) with 1,000 Hz dark count rate (DCR) and 20% SPDE w/ <200Hz DCR. Off the shelf micro lenses were acquired and initial testing on SiC APDs tailored to their layout showed a nearly four-fold

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Report Title

SiC Deep Ultraviolet Avalanche Photodetectors

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List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Handin Liu, Dion Mcintosh, Xiaogang Bai, Huapu Pan, Mingguo Liu, Joe C. Campbell, and Ho Young Cha, “4H-SiC PIN Recessed-Window Avalanche Photodiode with High Quantum Efficiency,” IEEE Photon. Tech. Lett., vol. 20, no. 18, pp. 57-59, 15 Sept. 2008.

2. Xiaogang Bai, Han-Din Liu, Dion C. McIntosh, and Joe C. Campbell, ”High-detectivity and high-single-photon-detection-efficiency 4H-SiC avalanche photodiodes,” IEEE J. Quantum Electron, vol. 45, no. 3, pp. 300-3003, March 2009.

3. Han-Din Liu, Huapu Pan, Chong Hu, Dion McIntosh, Zhiwen Lu, J. Campbell, Yimin Kang, and M. Morse, “Avalanche photodiode punch-through gain determination through excess noise analysis,” Journal of Applied Physics, vol. 106, no. 6, p 064507 (4 pp.), 15 Sept. 2009.

4. Han-Din Liu, Xiaoguang Zheng, Qiugui Zhou, Xiaogang Bai, Dion Mcintosh,and Joe C. Campbell, “Double Mesa Sidewall Silicon Carbide Avalanche Photodiode,” IEEE J. Quantum Electronics, vol. 45, no. 12, pp. 1524-1528, Dec. 2009.

5. Qiugui Zhou, Han-Din Liu, D. C. McIntosh, Chong Hu, Xiaoguang Zheng, and J. C. Campbell, “Proton-implantation-isolated 4H-SiC avalanche photodiodes,” IEEE Photonics Technology Letters, vol. 21, no. 23, pp. 1734-1736, 1 Dec. 2009.

6. A. V. Vert, S. I. Soloviev, J. Fronheiser and P. M. Sandvik, “Solar-blind 4H-SiC Single-Photon Avalanche Diode operating in Geiger-mode” IEEE Photonics Letters, 20, No. 18, p. 1587-1589, (2008).

7. Ho-Young Cha, Stanislav Soloviev, Scott Zelakiewicz, Peter Waldrab and Peter Sandvik, "Temperature dependent characteristics of nonreach-through 4H-SiC separate absorption and multiplication APDs for UV detection", IEEE Sensors Journal, 8, No. 3, p. 233-237, (2008)

8. Berechman, R.A., Skowronski, M., Soloviev, S., Sandvik, P.Electrical characterization of 4H-SiC avalanche photodiodes containing threading edge and screw dislocations (2010) Journal of Applied Physics, 107 (11), art. no. 114504

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10. Cha, H.-Y., Soloviev, S., Zelakiewicz, S., Waldrab, P., Sandvik, P.M. Temperature dependent characteristics of nonreach-through 4H-SiC separate absorption and multiplication APDs for UV detection (2008) IEEE Sensors Journal, 8 (3), pp. 233-237.

11. Loh, W.S., Ng, B.K., Ng, J.S., Soloviev, S.I., Cha, H.-Y., Sandvik, P.M., Johnson, C.M., David, J.P.R. Impact ionization coefficients in 4H-SiC (2008) IEEE Transactions on Electron Devices, 55 (8), pp. 1984-1990.

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(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

1. X. Bai, Han-Din Liu, D. McIntosh, and J. C. Campbell, ”High-performance SiC avalanche photodiode for single ultraviolet photon detection,” Infrared Systems and Photoelectronic Technology III, SPIE vol. 7055, 8 pages, ISSN: 0277-786X, San Diego, CA, Aug. 2008.
2. Xiaogang Bai, Dion McIntosh, Han-Din Liu, and Joe C. Campbell, “High Single Photon Detection Efficiency 4H-SiC Avalanche Photodiodes,” Proceedings of the SPIE - The International Society for Optical Engineering, Advanced Photon Counting Techniques, vol. 7320, April, 2009.
3. Gary A. Shaw, Andrew M. Siegel, Joshua Model, Adam Geboff, Stanislav Soloviev, Alexey Vert and Peter Sandvik, "Deep UV Photon-Counting Detectors and Applications", invited paper in SPIE DSS Conference Proceedings, Advanced Photon Counting Techniques III, Paper 7320-18, (2009)
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6. Stanislav Soloviev, Alexey Vert, Jody Fronheiser and Peter Sandvik, “Solar-Blind 4H-SiC Avalanche Photodiodespresented at the 2008 European Conference on Silicon Carbide and Related Materials.
7. A. Vert, S. Soloviev, J. Fronheiser and P. Sandvik, “Influence of Defects in 4H-SiC Avalanche Photodiodes on Dark Count Probability”, presented at the 2008 European Conference on Silicon Carbide and Related Materials.
8. Green, J.E., Loh, W.S., David, J.P.R., Tozer, R.C., Soloviev, S.I., Sandvik, P.M. Characterisation of low noise 4H-SiC avalanche photodiodes (2010) Materials Science Forum, 645-6648, pp. 1081-1084
9. Vert, A., Soloviev, S., Sandvik, P. Performance of silicon carbide avalanche photodiode arrays and photomultipliers (2010) Materials Science Forum, 645-6648, pp. 1069-1072.
10. Soloviev, S., Vert, A., Bolotnikov, A., Sandvik, P. UV SiC avalanche photodetectors for photon counting (2009) Proceedings of IEEE Sensors, art. no. 5398378, pp. 1897-1900.
11. Bolotnikov, A., Soloviev, S., Vert, A., Rowland, L., Sandvik, P. Numerical simulation of 4H-SiC deep and vacuum UV photodetectors (2009) 2009 International Semiconductor Device Research Symposium, ISDRS '09, art. no. 5378050,
12. Vert, A., Soloviev, S., Bolotnikov, A., Sandvik, P. Silicon carbide photomultipliers and avalanche photodiode arrays for ultraviolet and solar-blind light detection (2009) Proceedings of IEEE Sensors, art. no. 5398381, pp. 1893-1896.
13. Loh, W.S., David, J.P.R., Soloviev, S.I., Cha, H.-Y., Sandvik, P.M., Ng, J.S., Johnson, C.M. Avalanche multiplication and impact ionisation in separate absorption and multiplication 4H-SiC avalanche photodiodes (2009) Materials Science Forum, 600-603, pp. 1207-1210.
14. Soloviev, S., Sandvik, P., Vertiatchikh, A., Dovidenko, K., Cha, H.-Y. Observation of luminescence from defects in 4H-SiC APDs operating in avalanche breakdown (2009) Materials Science Forum, 600-603, pp. 1211-1214.
15. Vert, A., Soloviev, S., Fronheiser, J., Sandvik, P. Solar-blind single-photon 4H-SiC avalanche photodiodes (2009) International Journal of High Speed Electronics and Systems, 19 (1), pp. 85-92.

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(c) Presentations

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

1. Qiugui Zhou, Dion McIntosh, Han-Din Liu and Joe C. Campbell, “Proton-Implantation-Isolated Separate Absorption Charge and Multiplication 4H-SiC Avalanche Photodiodes,” IEEE J. Quantum Electron., submitted.
2. Alexey Vert, Stanislav Soloviev and Peter Sandvik Advances in Silicon Carbide Single Photon Detectors, Submitted to European Conference on SiC and Related materials, Norway, Sep 4, 2010

Number of Manuscripts: 2.00

Patents Submitted

Patents Awarded

Awards

LEC-2008 Best paper Award for the paper
Vert, A., Soloviev, S., Fronheiser, J., Sandvik, P. Solar-blind single-photon 4H-SiC avalanche photodiodes (2009)
International Journal of High Speed Electronics and Systems, 19 (1), pp. 85-92

Graduate Students

NAME	PERCENT_SUPPORTED
Qiugui Zhou	1.00
D. C. McIntosh	1.00
Kejia Li	1.00
FTE Equivalent:	**3.00**
Total Number:	**3**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Xingyi Guo	1.00
Han-Din Liu	1.00
A. L. Beck	1.00
Xiaogang Bai	1.00
FTE Equivalent:	**4.00**
Total Number:	**4**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Joe Campbell	0.07	No
FTE Equivalent:	**0.07**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

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The number of undergraduates funded by this agreement who graduated during this period: 0.00

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The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Global Research

SiC Deep Ultraviolet Avalanche Photodetectors

Final Report
October, 2010

Submitted to U.S. Army Research Office

Contract No.: W911NF-06-C-0160

Principal Investigator: Peter Sandvik (GE Global Research)
Lead Sub-Contractor: Prof. Joe Campbell (University of Virginia)

Executive Summary

The Department of Defense has strong interest in realizing small, reliable, cost-effective photodetectors, with high sensitivity and solar blindness for various applications including bio-aerosol detection, micro flash ladar for navigation, deep-UV imaging, and others. A discussion on these and other applications may be found in [1].

Photoemissive detectors such as PMTs and their variants have been the only viable technology for photon-counting in the deep UV. While PMTs exhibit extremely low dark count rates and large active area, they are bulky, fragile, and require optical filtering rendering their quantum efficiency to be very low. To address the DoD needs, original requirements set forth in the DARPA DUVAP program included detectors exhibiting: 6 OD solar rejection, 60 degree field of view (FOV), Geiger mode operation at 280 nm, large active area (1 cm^2), as well as low dark count rates and high quantum efficiency.

To achieve this goal, the DUVAP program was divided in three phases. The primary goal of the first phase was to demonstrate feasibility of Geiger mode operation of single UV avalanche photodetectors. Two material systems were explored: gallium nitride or GaN (multiple program performers) and silicon carbide or SiC (General Electric together with the University of Virginia). In the latter, GE's role was to focus on APD design, full-wafer fabrication development and yield assessment as well as Geiger mode device characterization, whereas UVA's role included exploring novel device structures, novel fabrication methods and studying the detailed physics of APD performance for feedback and iteration with GE. SiC, being a significantly more mature material than GaN, was successful in demonstrating Geiger mode APDs with good FOV, and reasonable quantum efficiency (>40% peak). As SiC has an indirect bandgap, optical filters were applied to the devices in order to block irradiance outside the solar blind window from reaching the active area of the device and thereby generating photocurrent. This work furthered the progress with the demonstration of devices with over 4 OD solar blindness with an integrated filter, and >6 OD when an external filter was applied.

In phase 2, the focus shifted to developing arrays of APDs to address the active area requirement as well as the design and integration of read-out integrated circuits (ROICs), the latter being done in a separate program by MIT-Lincoln Labs (running in parallel). During the second phase program, both 4x4 and 8x8 SiC APD arrays have been demonstrated with world-record single photon detection efficiency (SPDE) and dark count rate (DCR). A summary of progress up to about mid-2009 may be found in [2], as well as in the yearly August reports submitted through ARO. Since that time, further advancements have been made with initial work exploring micro-lenses to enhance APD array performance, as well as the demonstration of APDs with 40% single photon detection efficiency (SPDE) with 1,000 Hz dark count rate (DCR) and 20% SPDE w/ <200Hz DCR. These are also best performance results as identified by GE in the literature to date for this technology. The best performing SiC APD arrays made by GE Global Research, will be integrated into specially designed ROICs from MIT-LL for a system-like demonstration. This is expected by the end of 2010.

The original goal of a phase 3 program was to: optimize the design of the APD arrays, demonstrate novel integration techniques for optics to improve the effective fill factor as well as optimize the ROICs for SiC APDs and perform a system demonstration(s). While initial work towards these goals has been started, the other key phase 3 task of transitioning the detector technology to a DARPA specified partner will not see development as it has since been determined that phase 3 of the DUVAP program will not go forward.

Program Objective and Technical Need

As identified in DARPA's BAA06-14, DUVAP's stated goals were to develop novel photodetector technology towards general bio-fluorescence and NLOS communication based needs. Avalanche photodiodes working in the solar blind window (about 240 to 280 nm) were the development focus, with a desired goal of achieving compact, high efficiency, low noise, robust APDs capable of high gain or Geiger mode operation.

Since the release of BAA 06-14, the applications originally discussed were de-emphasized with a more general goal of attaining large area (via detector arrays) uniformity of Geiger mode performance. Key to these goals was achieving a high SPDE with a low DCR, while optimizing the fabrication process for suitable yield to facilitate large area arrays. Further improvements subject to study were the integration of APD arrays with optics such as microlenses, which may serve to enhance light collection and therefore effective fill factor of the array. Such developments lead to a broader applicability of these detectors, and guidance on device specifications for military applications was given by either DARPA or MIT-Lincoln Labs, who have a parallel project on-going. See ref. 1 for examples of applications and SiC detector performance.

Program Description and Milestones

The following objectives were called out in the original GE-UVA DUVAP program proposal:

1. Optimizing crystal growth and APD design using multiple modeling tools and device fabrication trials and testing to achieve low dark current near breakdown, high unity-gain external quantum efficiency, and high spatial uniformity.
2. Extending work on linear-mode device operation to develop single-photon-counting Geiger-mode detectors.
3. Developing and integrating optical filters to achieve very a high solar photon rejection ratio while maintaining high solar-blind detection efficiency.
4. Improving material uniformity and fabrication yield so large area arrays can be realized for integration into an NLOS system.

The following lists the milestones as identified in the 2006 proposal by the GE-UVA team. At 9 months from the beginning of the program:

- Optimized APD designs with a p-i-n structures (Task 1)
- Wafers with optimized p-i-n structure epitaxy (Task 2)
- Performance assessment of p-i-n structure SiC APDs (Task 3)
- Trade-off comparison of optical filter design approaches (Task 4)

At 18 months from the start of the program:

- Optimized APD designs with SACM structures (Task 1)
- Wafers with optimized SACM structure epitaxy (Task 2)
- Performance assessment of linear- and Geiger-mode SACM APDs (Task 3)
- Down-selection of optical filter approach (Task 4)
- Demonstration of APDs with integrated filters (Task 4)
- Go/no-go decision: SiC APDs have demonstrated feasibility for NLOS system capability

At 27 months from the start of the program:

- Wafers with optimized epitaxy for SACM-based APD arrays (Task 2)
- Performance assessment of APD arrays with integrated optical filters (Task 5)
- Trade-off comparison of array packaging approaches for feasibility demonstrations (Task 5)

At 36 months from the start of the program:

- Optimized SiC APD arrays demonstrating performance facilitating an NLOS system demonstration (Task 5)
- Arrays from Task 5 may be made available for independent assessment and feedback by DARPA designated contractors (Task 5)
- Go/no-go decision: SiC APD arrays have demonstrated feasibility for NLOS system capability

Scientific and Technical Results and Accomplishments

As the criterion goals of the APDs' and arrays' performance were left somewhat general, a careful design, fabrication, test and evaluation loop was instituted to gain strong insight into the device design choices. Towards the initial goals stated above, the GE-UVA team met largely with success.

With regard to the first goal, a GE team studied various metalorganic chemical vapor deposition-based conditions to optimize APD structure morphology and structure. These developments, done on a single-wafer research reactor, served as a guide for the team to ultimately model, iterate and settle on the multi-layer separate absorption and multiplication (SAM) or separate absorption, charge and multiplication (SACM) region design SiC APD, for example, see [3]. For APD arrays and latter optimization in phase 2 of the program, the team largely used commercially available SiC epitaxy made to specification. To the second and third goals, SiC APDs with low leakage up to the onset of breakdown were made for linear mode operation in phase 1, at which point, the team was directed by DARPA to focus on Geiger mode operation of the detectors. Here, a Geiger mode detector test capability was developed to evaluate the best yet designs. The team reviewed progress with ARO and DARPA at this time to positive feedback, including a demonstration of low-noise Geiger mode operation with an integrated optical filter. The filters were designed in concert with Barr Associates (Westford, MA), and ultimately deposited by Barr, resulting in good large area uniformity in phase 1, which had design optimizations in phase 2. In the fourth stated goal, whole three inch diameter SiC wafers were used in the fabrication of SiC APDs and arrays with device breakdown voltage yields on some wafers reaching greater than 80%. Combined with high uniformity optical filters, arrays with over 80% of the detectors working were demonstrated both in single device mode, but also in the mode of a photomultiplier [4]. A more detailed accounting of the team's progress may be found in the annual August reports submitted to ARO for the DUVAP program.

To the stated goals, the first phase (18-month) goals were reached sufficiently as determined by ARO and DARPA, thereby granting passage to a second phase of DUVAP. It is noted that the p-i-n structure was developed in concert with the SACM design, however the SACM design offered greater performance potential with the trade-off of a slightly more complex production approach. Therefore, the second phase program dealt mainly with SACM design devices and their optimization into detector arrays. Arrays were thus designed and their designs iterated upon with key criterion in mind such as high fill factor, larger areas desired, ease of packaging and implementation and integration with micro-lens arrays. Several of the design choices used in the latter portion of phase 2's program were made with the help of MIT-LL, who retained key application expertise and knowledge, as they work towards a system demonstration using GE-UVA-made SiC APDs and arrays.

The GE-UVA team also lists the following accomplishments from the DUVAP program:

- APD designs were evaluated and optimized using optical and electrical device simulations, and associated fabrication methods for solar-blind SiC APD arrays have been developed. Absorption coefficient properties were derived from iteratively made APD structures for SiC, and subsequently used to speed device improvements [5] by predicting UV and solar blind optical behavior. Figure 1 shows a schematic cross section of the developed SiC APD.

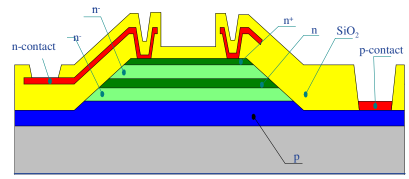

Figure 1. Schematic cross-section of SiC APD.

- Novel fabrication processes required for this program included controlled sidewall etching of the APDs, the integration of thin film optical filters and array layout design. These were used to attain low leakage APDs with effective suppression of sidewall leakage current. Figure 2 shows an SEM image of APD array 8x8.

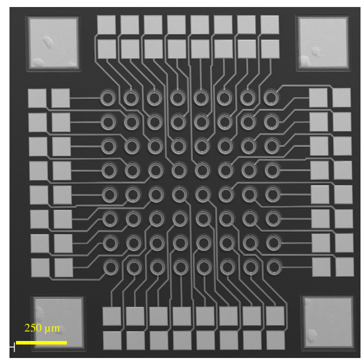

Figure 2. SEM image of APD array 8x8.

- SiC ionization rates were studied in an in-kind collaboration with Sheffield University. These studies have made new determinations of ionization rates for SiC over a wide temperature and electric field range, and have enabled subsequent device modeling work to be increasingly accurate [6].

- SiC APDs operating at a wavelength of 280 nm with the effective Geiger mode gain of 10^6 have been demonstrated. A dark current density of ~20 nA/cm^2 at a gain of 1000 was achieved in the best devices. Figure 3 shows a yield map and yield distribution of the best devices on a SiC wafer. Cumulative yield of SiC 4x4 arrays with more that 80% of devices per array demonstrating a dark count rate of <~1kHz at gain of ~10^6 was ~70%.

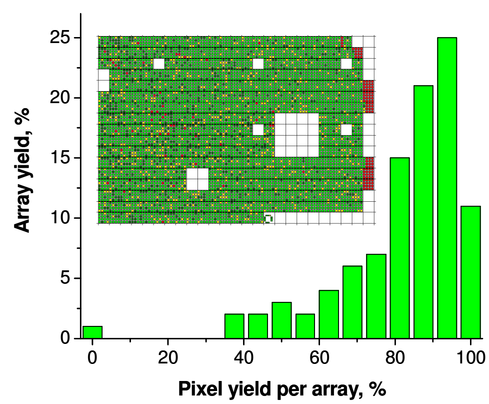

Figure 3. Yield map and yield distribution of the best devices on a SiC wafer

- Thin film, dielectric stack filters were selected from a study of available technologies as they afforded device integration and flexibility in design. Optimum filters were about 5 μm thick and comprised of about 100 layers, and were successfully integrated onto SiC APDs. A solar rejection ratio between 280 nm and 320 nm was 5×10^4 for the integrated filter and 5×10^5 for an external filter, when deposited onto an optically polished sapphire substrate. Devices with external and integrated solar blind filters showed rejection ratio of at least 10^6 for visible photons, but the rejection ratio of near-UV photons was slightly lower than expected in devices with integrated filter due to small but appreciable surface roughness on the device. Figure 4 shows spectral responses of APD detector with filters and SEM cross-section of dielectric stack filter.

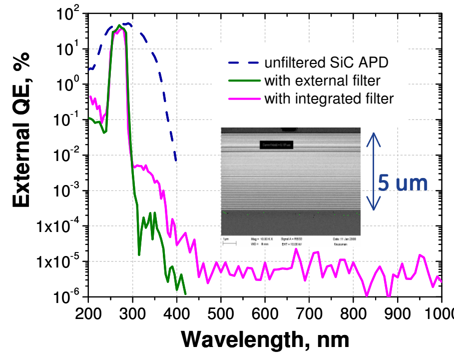

Figure 4. Spectral responses of APD detector with filters and SEM cross-section of dielectric stack filter.

- GE SiC Solar blind detector demonstrated the best response in deep UV spectral region and better solar rejection ratio than Perkin Elmer and Hamamatsu detectors. Figure 5 shows the external spectral response of the typical SiC APD device with the solar blind filter. The spectral sensitivity is compared to currently available solar-blind detectors on the logarithmic scale. Note, Si detector provides a better ratio due to much expensive and much thicker OFIL filter .A sharp roll-off of the sensitivity above 300nm, high sensitivity in the ultraviolet portion of the spectrum and high visible photons rejection ratio makes GE SiC-based detectors one of the most efficient and cost-effective detectors for solar-blind light detection.

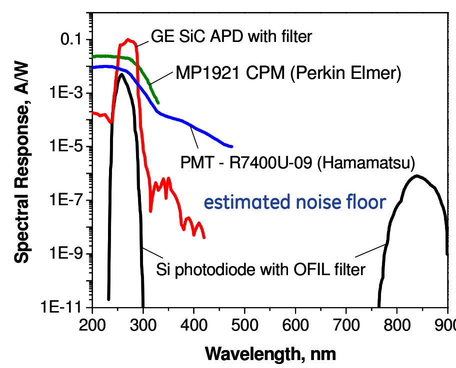

Figure 5. State-of the-Art of solar-blind detectors

- Measurements of the dielectric stack filters also confirmed that a 60 degree FOV is achievable for the current design. Thicker filters improve cutoff sharpness, however, further restrict FOV.

- Quantum efficiency of ~50% (280nm) was demonstrated with high solar (4 OD) and visible (5.5 OD) rejection ratio using an integrated filter.

- Array designs were fabricated, tested and improved resulting in 4x4 and 8x8 element arrays with appreciable device yield, as measured across the wafer. A 4x4 element version of this design was selected for ROIC design and integration by MIT-LL and initial testing on single APDs confirmed baseline functionality.

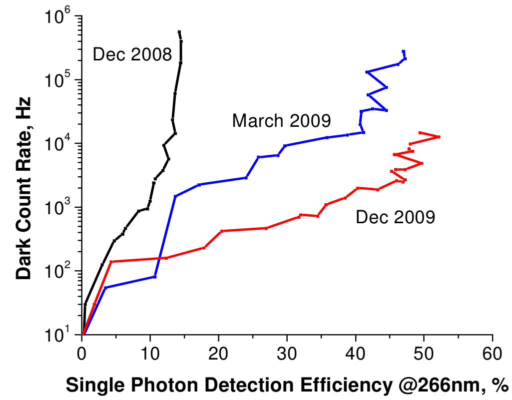

Figure 6. Plots of dark count rate versus the single photon detection efficiency for APD devices fabricated in the program

- Figure 6 shows plots of dark count rate versus the single photon detection efficiency for APD devices fabricated in the program. A single photon detection efficiency (SPDE) of 40% with 1,000 Hz dark count rate (DCR) and 20% SPDE w/ <200Hz DCR was demonstrated.

- Off the shelf micro lenses were acquired and initial testing on SiC APDs tailored to their layout showed a nearly four-fold increase in photoresponse, but with a narrower field of view of about +/- 20 degrees as shown in Figure 7.

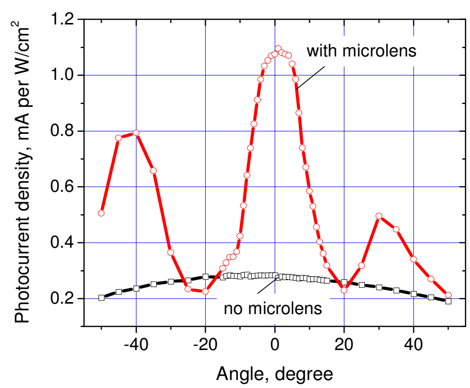

Figure 7. Photoresponse of APD array with and without microlens optics vs. angle of incident light.

Application and Considerations for the Future

The SiC APDs and arrays developed under this program may be applied to the applications identified in the original DUVAP BAA, or those for general DoD or industrial use. While GE will continue to evaluate potential industrial applications for this technology, following the completion of phase 2, no continuing activity is currently planned.

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